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Final Report

MICROWAVE DEVICE TECHNIQUES FOR AEROSPACE SURVEILLANCE

M. Chodorow
et al

Stanford University
Microwave Laboratory

TECHNICAL REPORT NO. RADC-TR-68-302
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Rome Air Development Center
Air Force Systems Command
Griffiss Air Force Base, New York

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FOREWORD

This final report was prepared by the Microwave Laboratory, W. W. Hansen Laboratories of Physics, Stanford University, Stanford, California under Contract AF30(602)-3595, Project 5573, Task 557303, covering the period November 1964 through October 1967. The report is identified by the contractor as M.L. No. 1646.

RADC Project Engineer was William E. Wilson, (EMATE).

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This technical report has been reviewed and is approved.

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ABSTRACT

The objectives for the research program under this contract were to conduct a theoretical and experimental investigation of microwave techniques with a view toward development of devices applicable to surveillance systems; the emphasis was primarily directed toward requirements of phased array radar systems. This report, covering the period November 1964 through October 1967, summarizes the principal research findings on the following projects, conducted for varying lengths of time on this contract:

I. Thin Film Transducers
II. Acoustic Wave Devices
III. Carrier Wave Propagation
IV. Whistler Mode Propagation in Solids
V. Theory of Carrier Wave Propagation
VI. Extended Interaction Klystrons
VII. Centipede TWT
VIII. Periodic Ferrite Delay Lines
IX. Adiabatic Magnetoelastic Conversion in the Time Domain
X. Theory of the Gunn Effect
XI. Guided Acoustic Waves
XII. Delay Line Studies
XIII. Magnetically Dependent Sound Wave Interactions

Future reports concerning the projects to be continued will be found in reports on Contract F30602-68-C-0074, "Microwave Acoustic and Bulk Device Technique Studies" which is a direct continuation of this effort.

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EVALUATION

1. The objective of this contract, a direct follow-on of AF30(602)-2575, "Multimegawatt Broadband Microwave Tubes" was to investigate new concepts for the generation and control of microwave energy for application to large ground-based multi-element array radars. Some high power tube work carried over from the predecessor contract, but by-in-large, the investigations were confined to microwave solid-state devices using the electronic and mechanical properties of bulk and thin film materials.

2. Particularly notable were the contractor's efforts in the field of microwave acoustics where vast strides were made in improving the state-of-the-art of bulk acoustic microwave transducers by the deposition of thin (half wave length) active (piezoelectric) and passive (conductive or impedance matching) films. Insertion losses of as low as 3 db over a narrow bandwidth using CdS and 13 db over very wide bandwidths using ZnO have been demonstrated. To date, the contractor still leads the state-of-the-art in this area and is pioneering work in the deposition of thin films of new materials having vastly improved acoustic capability.

3. A considerable amount of theory has been produced in other areas of microwave acoustics (including magnetoelastic phenomena in ferrimagnetic insulators and surface wave propagation in piezoelectric materials), in electromagnetic wave transport and instability phenomena in semiconductor, and in high power microwave tube circuitry by the investigators and students working under them. A complete bibliography of reports and publications resulting from the contract is listed in pages 9 thru 13 of the final report. Many of the ideas discussed in this publication have been subsequently investigated further by industrial concerns active in the respective fields. Some of the work listed within is being further pursued on F30602-68-C-0074 "Microwave Acoustic and Bulk Device Technique Studies" which is a direct continuation of this effort.

William E. Wilson
WILLIAM E. WILSON
Project Engineer
Electron Devices Section

INTRODUCTION

This report is intended to summarize briefly the activities of the Microwave Laboratory under Contract AF 30(602)-3595 for the period November 1, 1964 through October 31, 1967.

During the course of this contract, a large number of quarterly reports, technical reports and publications have been issued which described in considerable detail all of the work done under this contract. This report is merely a summary of the various topics which have been investigated. Since the main body of this report consists largely of separate items concerning each of the separate topics which have been investigated, it may be of some value here to review the program in a somewhat broader context to point out the main directions of activity, what the principal contributions have been, and what this may imply for future work under successor contracts. As a subsidiary function, which may be useful in providing background for this report, we will also include here a brief history of the work done under the predecessor contract.

In this introduction, therefore, we shall start with this historical background as, in some ways, it clarifies some of the reasons for the directions of the work undertaken and reported herein. This is of particular significance since the current contract represents an important transition from a long history of research in microwave tubes into new areas which were important to the interests of RADC, and which seemed to require considerable research effort and the consideration of some new concepts.

For a number of years, under the predecessor contracts, the Microwave Laboratory undertook extensive investigations in high power microwave tubes and particularly, in more recent years, high power traveling wave tubes. We shall not attempt to adhere to a strict chronology, but merely wish to emphasize some of the activities under these contracts, some of the accomplishments, and their historical connection to the present contract.

The first major activity undertaken at the Microwave Laboratory for RADC was the development of a pulsed L-band klystron, jointly with Litton Industries. The contribution of the Microwave Laboratory was to provide the electrical design, to build some preliminary models, test them, and assure satisfactory electrical performance. This is the tube which is now known as the L3035. Litton was to provide the mechanical design in such form that they could take over the program after the initial development and go into production. The laboratory built something in the order of a dozen tubes. The program has been successful, and has been considered by all concerned as an outstanding example of collaboration between an academic research laboratory, the government, and industry.

Subsequent to this, the laboratory under RADC auspices began to turn its efforts toward pulsed traveling wave tubes operating in the range of several megawatts. It was felt that the skills and experience available in the Microwave Laboratory with pulsed klystrons could be transferred in a useful way to high power traveling wave tube work, and such a program was initiated. There had been an earlier program in the Microwave Laboratory under a Joint Services contract which had already done some preliminary investigation of traveling wave circuits which were suitable for pulsed traveling waves, and this preliminary work was then continued in a more extended and directed way under RADC auspices. It is difficult to pinpoint exactly at what stage the program was transferred from other auspices to RADC, or to draw a sharp dividing line between the previous activities in this field in the Microwave Laboratory and that done with RADC. However, it is certainly true that the principal contribution in this country to the development of pulsed traveling wave tubes of the kind which are now being widely used in systems was achieved in the Microwave laboratory under the auspices of RADC.

We list here some of the circuits that were developed, some of the problems that were solved in connection with opening up the whole field of pulsed traveling wave tubes, and the present impact of this work.

Circuits which were first invented or developed at the Microwave Laboratory and largely brought to the point of practicality under RADC auspices included the centipede structure, the cloverleaf structure, the long slot structure, the crosswound helix (and related circuit, the ring bar circuit), and also the coupled cavity circuit.

The coupled cavity circuit was first worked on extensively at the Stanford Microwave Laboratory. It was used here in the first traveling wave tube ever run at peak powers of hundreds of kilowatts and then later also at something over a megawatt. Modified versions of this circuit are now widely used at lower power levels either cw or pulsed in tubes operating in the range of 10 to 100 kilowatts, particularly in the X-band region. Probably all of the traveling wave tubes used for satellite ground stations use this circuit at present.

The crosswound helix, or ring bar circuit, invented at the Stanford Microwave Laboratory was extensively investigated and its unique properties demonstrated here. It is now the principal circuit used for pulsed operation at ten to several hundred kilowatts, particularly where either wide band and/or low frequency operation is concerned. It is about the only available circuit for power up to, say, 100 kilowatts and for bandwidths above 10%, below S band. It is also used at lower peak powers at higher frequencies, when the bandwidths required are more than is conveniently achievable with the coupled cavity circuit mentioned above. The circuit is now used as the primary power source in some experimental phased array radars and as a driver tube for megawatt traveling wave tubes which require tens of kilowatts of drive.

The cloverleaf structure is the principal circuit currently used for traveling wave tubes operating above a megawatt of peak power. All the basic concepts, circuit parameters, matching, methods of attenuation, etc. were developed under RADC auspices at Stanford. The principal systems requiring powers in this range presently use this circuit or variations thereof, such as the twystron. Aside from operating systems using this tube, there are other important uses of this circuit for very high peak and average powers which are now in development.

The centipede, which is an alternative circuit to the cloverleaf, has been less extensively investigated. It was invented and built at the Microwave Laboratory under RADC auspices, and has demonstrated the highest bandwidth available in multimegawatt traveling wave tubes. It was successfully developed at the Microwave Laboratory, after the cloverleaf, in an attempt to obtain appreciably greater bandwidth. In many applications, however, the bandwidth achievable with the cloverleaf has been adequate, so most of the subsequent tube development elsewhere has been made using the cloverleaf. If greater bandwidth is needed, the centipede seems to be the more likely candidate and RADC at this moment is actually having a centipede tube developed for this reason, in an industrial laboratory.

Aside from the high power traveling wave tube work, there was also considerable effort in investigating the so-called distributed interaction klystron in which cavities of the klystron have a geometry so that the electrons interact with a field over an extended region instead of in a narrow gap. The cavity can be a resonant section of a helix, or multiple coupled cavities, in each case the circuit being made resonant at the operating frequency. The extended interaction cavity has marked advantages, in terms of bandwidth and efficiency, over the conventional narrow gap cavity. These properties were first demonstrated under RADC auspices and this kind of cavity is now in use and being further developed under RADC auspices at various industrial laboratories.

We have presented only a bare outline of the earlier effort, pointing out merely some of the major accomplishments; but this represents the result of many years work by a number of people investigating many aspects of these and related problems. At the end of the program that has just been described, it was beginning to be obvious that the major portion of the continuing problems in microwave tubes were largely concerned with technology, with reliability, with objectives of going to higher peak and average power which involved materials, cooling, mechanical design and were more suited for industrial laboratories than for a university laboratory. There had also been a continual growth of

interest in the tubes and circuits developed at the Microwave Laboratory by many industrial laboratories which began to launch major efforts of their own in these areas and seemed to be working on the relevant problems in an adequate way.

Along with this shift in the nature of the problems in microwave tube research, it began to be apparent that the interests of RADC were also beginning to shift, particularly toward devices which would be relevant to phased arrays and, more specifically, to components such as delay lines, integrated amplifiers, etc., which could be used for the handling and transmission of information, for signal processing internally in phased arrays or in other radar systems, and which would be compact — that is, not using electron tubes. The class of physical phenomena which could be used for these purposes included acoustic waves at microwave frequencies, in insulators, magnetic materials, and piezoelectric materials, carrier conduction in semiconductors, and spin waves in ferrites. It is these phenomena and the associated devices which has absorbed a great amount of the activity of the Microwave Laboratory in recent years. The result has been that the Microwave Laboratory, during the period covered by this report, has changed the whole emphasis of its program under RADC auspices, the nature of its research, the type of technologies available in the Laboratory, the technical skills, and the detailed problems, from microwave tubes to the areas which have just been broadly described above. This shift is apparent from the listing of the research topics in the main body of the report. There are still vestiges of some tube activities reported, but these were the tail end of the tube activity and this report is largely concerned with activity in microwave acoustics, microwave semiconductor devices, and microwave ferrite devices.

It might be of value to summarize here some of the highlights of this new program, which is described in somewhat more detail in the body of this report, and in much more detail in the various references quoted in various portions of this report. Under the auspices of RADC, we have mounted a massive effort over the past several years in all aspects of

microwave acoustics. As a part of this we have developed all the specialized technology necessary for research in this field. This includes facilities for making thin film transducers, for polishing and orienting crystals, depositing films to be used in investigation of acoustic surface waves, bonding of various materials, and other related technology, all of which are concerned with acoustic devices for achieving some of the information handling objectives mentioned in the paragraph above.

There have been a number of important achievements which resulted from the availability of this technology, and this will also provide us with the base for our future activity. Among these achievements we might mention the work on thin film acoustic transducers in which one deposits various combinations of metal, insulator and piezoelectric films of suitable thicknesses on substrates so that they provide optimum transfer of energy from microwave cavities, or transmission lines, to acoustic waves in the substrate. We have made several unique contributions in producing such films using cadmium sulfide, zinc oxide and aluminum nitride as the piezoelectric materials and, as a result, we have achieved probably the lowest insertion loss transducers at microwave frequencies available anywhere. This includes 4 dB loss using CdS, and 6 dB with zinc oxide, and we have also opened up some new avenues for further work. The zinc oxide transducer was the result of the development of a new method of deposition which has been more successful than any other achieved elsewhere with this material. We have also had some success with the deposition of other promising piezoelectric films such as lithium niobate, but no transducer data is available yet.

In our work on amplification mechanisms we have been able to elucidate the instabilities which occur in certain piezoelectric semiconductors which can be used for acoustic amplifiers. These instabilities have been a barrier to making successful amplifiers, and our program has indicated the directions in which one should proceed to avoid the instabilities which have been so troublesome.

We have also started a very promising program on surface acoustic waves and guided acoustic waves in thin films. These also have utilized the thin film technology we have developed, and we expect this will lead to the use of guided acoustic waves in thin films on the surface of a substrate which can act as a miniaturized transmission line between the various parts of a microwave system. There is also the possibility, by depositing an overlying semiconducting film, to build acoustic amplifiers using the interaction between the carriers in the semiconductor and the surface waves or guided waves in piezoelectric media.

The work on ferrite delay lines using YIG primarily has opened up some completely new possibilities. In addition to inventing and/or developing several forms of two port YIG delay lines, which use magnetoelastic waves for the delay, we have also opened up a whole new range of possibilities by making time variable delay lines. This is accomplished by varying the external magnetic field applied to the YIG, after the signal to be processed has been injected. Under various possible circumstances, one can achieve variable delay, pulse compression, frequency shift, or pulse inversion of an injected signal. This opens up some exciting possibilities for information processing which we intend to pursue further.

We have also had an extensive program investigating various amplification mechanisms in various semiconductors, including gallium arsenide (Gunn effect). In this, we have made some significant contributions to the theoretical calculations of the large signal behavior of Gunn effect devices and also, both experimentally and theoretically, have been able to investigate some limitations on the amplitude of Gunn oscillations due to avalanching within the semiconductor.

We have also been investigating propagation of various waves in indium antimonide. Our efforts so far indicate several possibilities for either delay lines or amplifiers. On the one hand, we have investigated theoretically and have some preliminary experimental evidence of the possibility of producing so-called carrier waves in which the signal is carried by the electrons from one end of the crystal

to another, with high gain.* By another mechanism, there is indication that under suitable conditions, involving a dc magnetic field and an applied electric field, one can use indium antimonide as an acoustic amplifier. The significance of this would be that the voltage gradients required would be significantly lower than in other materials, such as CdS, which have been commonly used for acoustic amplifiers and that also the gain per unit length would be much smaller. This latter property has an advantage because this would imply that one could make amplifiers with long delays (through using long samples) without getting into instability problems. A delay line with gain and with long delay would obviously be an important device.*

We have touched here only on a few highlights of the work done under this contract. It is our intention to continue the work entirely in the areas which have just been described. Specifically, we intend to continue work on the broad problems of delay line mechanisms, and delay line devices including means incorporating amplification into delay lines and also on methods by which one can process a signal while it is in a delay line. The nature of such methods is indicated in some of the paragraphs above. This then will include work in microwave semiconductor devices, acoustic devices, acoustic amplifiers and phenomena, and ferrite devices. Broadly speaking our objectives will be to investigate phenomena and devices which are relevant to the transmission and processing of information with the restriction that the ultimate devices should be compact and if possible lend themselves to integration.

* It is worth noting that both these possibilities have been markedly successful in the successor contract.

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1. THIN FILM TRANSDUCERS

(D. K. Winslow, M. T. Wauk, J. Larson, and J. White)

A. INTRODUCTION

A very important approach to the realization of time delay at microwave frequencies is through the use of microwave acoustic waves in solids. In all such devices and applications of acoustic waves, one of the largest practical difficulties has been in the coupling loss in transducers designed to couple microwave electromagnetic energy into microwave acoustic waves.

In this program we set up facilities for the fabrication of new types of transducers, particularly employing thin film techniques, and constructed and tested numerous thin-film transducers assemblies. The objective was to fabricate working models of new approaches to transducer design and to test these designs in the laboratory by measurements of coupling loss, passband characteristics, and electromagnetic input impedance. We found that by the proper use of thin films we could obtain transducers of very low conversion loss.

B. SUMMARY OF WORK ACCOMPLISHED

Thin film transducers of four different piezoelectric materials were fabricated and evaluated. The cadmium sulphide (CdS) thin films with silicon monixide (SiO) and gold (Au) as quarter wave acoustic impedance transformers yielded measured conversion losses for longitudinal waves as low as 4 dB at 800 MHz.[1,2*] These films can be reliably reproduced, and were and are used in conjunction with many experiments in this laboratory. W

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* Note: The references cited here and throughout this report are to status reports prepared for the subject contract. Papers and publications pertinent to each project are listed at the end of each section.

developed an entirely new method for the deposition of zinc oxide (ZnO) films,[3-10] and they yielded low measured conversion losses at frequencies to 3 GHz over large bandwidths. Both aluminum nitride[8,10] (AlN) and lithium niobate[9,10] ($LiNbO_3$) were vacuum deposited as piezoelectric transducers for the first time, as far as is known. Both generated only longitudinal waves. Special vacuum deposition stations were designed and constructed for operating with CdS,[1] ZnO[3,7] and AlN.[8] In addition, five other stations were designed and constructed for special metal or dielectric films.[1,3,4,9] Measurement facilities for evaluating the various film structures are operating from 0.5 to 12 GHz.

Other important results of this program included the following: several other investigations of thin film transducers have been completed.[5,6] and shear wave transducers of about 20 dB at 1000 MHz were assembled.[5] Evaporated electrode films and special mounting techniques[1,3,6,10] were developed primarily to improve the electromagnetic circuit characteristics. Overcoupling between the electrical resonator and the acoustical thin film resonator was first observed in this laboratory.[3] Detailed chronological information on all these results are available in status reports for this contract. The important and relevant aspects of this program will be continued on the successor contract.

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II. ACOUSTIC WAVE DEVICES

PHASE I (C. F. Quate and W. H. Haydl)

A. INTRODUCTION

Two instabilities may occur in piezoelectric semiconductors due to the interaction between acoustic waves and drifting carriers. Since both instabilities involve the amplification of acoustic energy, they appear only above fields at which the carriers drift faster than sound. The first instability causes a decrease in the sample current, which occurs within a time of the order of microseconds. This "current saturation" is caused by the force a growing acoustic wave exerts on the carriers and the resultant change in the electric field distribution along the sample. Current saturation, we find, is observed at fairly low acoustic power densities. If higher acoustic power densities are approached, the second instability, which causes "current oscillations" and traveling high electric field domains, is observed.

B. RESEARCH SUMMARY

For the first time, potential probe measurements were made on CdS, resulting in the discovery of the traveling narrow regions of high electric field.[1] High field domains were discovered in both high resistivity photoconducting and low resistivity semiconducting CdS. In the case of semiconducting CdS, the field inside the domain is of the order of 3×10^4 volts/cm, the domain width is 10-100 microns, and the velocity of the traveling domain was found to be equal to the shear wave velocity, which is 1.75×10^5 cm/sec.

We believe that the traveling high field domain is caused by a negative differential bulk conductivity when an acoustic signal reaches power densities which are of the order of watts/cm^2. The negative differential bulk conductivity may exist because of the force exerted on the carriers by an acoustic wave under conditions of amplification. The traveling high field domain is observed to form when the acoustic energy reaches a fairly well defined level. The traveling high field domain consists of an accumulation

and a depletion layer of mobile charge carriers. Experimental evidence indicates that an extremely high intensity pulse of acoustic energy accompanies the domain, forcing it to travel at the sound velocity.

Current saturation and current oscillations are very dependent on the resistivity of the piezoelectric semiconductor. Current saturation is most pronounced in materials having a resistivity of the order of 10^3-10^4 ohm/cm. Current oscillations are large in highly conducting material (0.01-100 ohm/cm) and decrease in magnitude as the resistivity increases.

Square-wave type current oscillations and the traveling high electric field domains in cadmium sulfide were discovered and studied. Numerous experiments were performed to determine the behavior of the traveling domain, the oscillation conditions and important parameters. Experimental results lead to the conclusion that both current saturation and current oscillations as observed are due to amplification of the shear wave components of thermal acoustic noise.

Some further details on this work are available in RADC-TR-65-348 (M.L. Report No. 1349), first regular status report for the contract. A comprehensive presentation of all the work on this project, including the research performed after it was transferred to another contract, is in the dissertation of W. H. Haydl, "Current Instabilities in Piezoelectric Semiconductors," Stanford University (March 1967).

PHASE II (C. F. Quate, R. B. Thompson, and B. Richardson)

A. INTRODUCTION

When the work of Phase I above was transferred, this project shifted its focus to the examination of various systems of parametric amplification of acoustic waves. A system in which acoustic waves could be transmitted through a suitable crystal without loss would, in our view, remove a fundamental limitation of acoustic delay lines. Such interactions should also provide a method of generating high intensity sound columns in a most efficient way.

We studied a family of problems associated with the parametric pumping of a strain wave by either a strong electromagnetic or strain wave. Various nonlinearities in both insulating and semiconducting crystals have been considered as a means of coupling the waves.

B. RESEARCH SUMMARY

1. Insulating Crystals

In certain insulating crystals, the elastic nonlinearities offer a means of amplifying a strain wave by a strong strain wave pump.[9] These nonlinearities were extensively studied in three materials:[7] quartz, MgO, and MnFe. Sinusoidal waves (typically at 500 MHz with a strain of 10^{-5}) were excited by transducers at the end of the crystals. As the waves propagated through the medium, they rapidly became deformed and the following effects were observed: variation of the attenuation of the fundamental with power level, the presence of second through fifth acoustic harmonics, and the growth and decay of these harmonics as a function of distance traveled by an acoustic pulse. These phenomena were all satisfactorily related to the acoustic nonlinearities.

2. Semiconducting Crystals

In piezoelectric semiconducting crystals,[3,4,5] the necessary nonlinearity is provided by the drifting carriers; each acoustic wave is accompanied by a carrier wave due to the piezoelectric property of the medium. The electric field can directly interact with this carrier wave. Calculations have indicated the form of the interaction to be highly promising, although the fabrication of the experiment is currently a problem. This amplification scheme appears to be of greater promise than the one for insulating crystals. The nonlinearities are of large enough magnitude so that significant amplification can be observed for readily obtainable pump. The other schemes are currently limited by available pump powers and nonlinearities.

PAPERS AND PUBLICATIONS

W. H. Haydl and C. F. Quate, "Current Oscillations in Piezoelectric Semiconductors," Microwave Laboratory Report No. 1446, Stanford University (June 1966); also published in J. Appl. Phys. 38, 4295-4309 (October 1967).

R. B. Thompson, C.D.W. Wilkinson, and B. A. Richardson, "Finite-Amplitude Acoustic Waves in Crystalline Solids," Microwave Laboratory Report No. 1561, Stanford University (July 1967); submitted to J. Acous. Soc. Am. and presented at the 73rd Meeting of the Acoustical Society of America (April, 1967), Paper PW8.

III. CARRIER WAVE PROPAGATION

(G. S. Kino and J. Owens)

A. INTRODUCTION

The inherent instability associated with a bulk negative resistivity has been the object of considerable study. Negative resistivty occurs when the current decreases with increasing electric field. The two types have been termed the current controlled and voltage controlled differential negative resistivity. Current controlled negative differential resistivity is one in which for a given electric field the current can have multiple values. The common example of this type is a gas discharge. In a gas discharge the current is linear at low fields, and as the field increases ionization begins and resistance drops. Thus, to maintain a constant current, a lower field is required. This is a negative resistance characteristic. The voltage controlled negative differential resistivity is one in which for a given current the electric field can have multiple values. A well known device which exhibits a voltage controlled negative resistivity is the Esaki or tunnel diode. From the experimental work of Gunn, and the previous work of Ridley, it has become evident that semiconductors can exhibit a voltage controlled negative differential resistivity throughout the bulk of the material. This case is quite different from the tunnel diode, in that one must consider the spatial variation of fields and charge throughout the sample. It was our purpose to study in detail the structure of the "high field domain" generated in materials which exhibit bulk negative differential resistivity.

B. RESEARCH SUMMARY

Theoretical calculations were carried out using the most recent velocity field characteristics and diffusion field characteristics of Ruch and Kino. The results show considerable differences from earlier calculations. From the characteristics of the domains, the domain potentials required for avalanching were calculated and from these results

the inherent limitation imposed by avalanching was analytically specified.[9] We also carried out experimental studies designed to complement the theory. Avalanching within the domain was observed,[8] and the characteristics of the radiation from this avalanching was studied.[7] Capacitive probe measurements were made on the domains to study the propagation characteristics. Finally, the effects of sustained high domain potential were studied in detail.[8]

We feel that the correlation between the theory and experiment is good. We can now accurately predict the avalanching characteristics of Gunn oscillators and its consequent limitations. A comprehensive report on this project is now in preparation and should be completed in the near future; full details on the theory and research will be presented.

PAPERS AND PUBLICATIONS

J. M. Owens and G. S. Kino, "Multiple Current Spiking in Long Gunn Oscillators," Microwave Laboratory Report No. 1468, Stanford University (September 1966); also published in Phys. Letters 23, 453-455 (November 1966).

J. G. Ruch and G. S. Kino, "Measurement of the Velocity Field Characteristic of GaAs," to be published in Appl. Phys. Letters (January 1968).

IV. WHISTLER MODE PROPAGATION IN SOLIDS

(G. S. Kino, J. C. Eidson, J. Shaw, and B. Burke)

A. INTRODUCTION

Helicons, i.e., the whistler or helicon mode of electromagnetic wave propagation, can propagate through a solid along a dc magnetic field at frequencies below the carrier cyclotron frequency and are damped in a distance which depends on the carrier mobility and magnetic field. The requirement for low loss propagation is easily achieved in pure n-type InSb at 77°K and fields of a few kilogauss; thus this material was chosen for all of our experiments.

B. RESEARCH SUMMARY

Initial experiments with helicons involved the transmission of 55 GHz signals through a thin slab of InSb. We observed the dimensional resonances of the slab seen by others in the cases where helicon propagation was parallel and perpendicular to the magnetic field. Comparison of theory with our measurements yielded satisfactory agreement,[1] and we began planning the more sophisticated experiments with helicons described below.

At this time reports appeared in the literature of microwave emission from InSb subject to electric and magnetic fields at 77°K. These experiments were repeated in this Laboratory, and some important new observations were made. The noise emission was found to extend from 30 MHz to beyond X-band and could be seen at low electric fields ($\sim$ 10 v/cm) and magnetic fields as low as 2 kilogauss. We reported the first observation of single frequency emission at S-band from InSb; the oscillations were voltage tunable and had power levels 10 to 20 dB above receiver noise (-90 dBm). A paper concerning the details of this phenomenon appeared in Applied Physics Letters (Eidson and Kino). Subsequent measurements revealed further narrow band oscillations of higher power (-40 dBm) at lower frequencies (0.1 - 1.0 GHz).[4,5]

While the origin of the noise and coherent emission remained a mystery, theories were advanced which suggested that a helicon-drift current interaction might be responsible. We then began careful and detailed measurements of the phase velocity and attenuation of two helicon modes propagating along cylinders of InSb at S-band frequencies. The measurements were among the first in semiconductors to demonstrate the effects of boundaries on guided helicon propagation, and yielded very good agreement with existing theories. Drift currents were applied to the sample to see if an amplifying interaction was present, but none was observed even for electric fields far above the noise emission threshold. The details of these measurements[6,7] were presented at a conference and were also published (Burke and Kino).

PAPERS AND PUBLICATIONS

J. C. Eidson and G. S. Kino, "A New Type of Oscillation in Indium Antimonide," Microwave Laboratory Report No. 1402, Stanford University (January 1966); also published in Appl. Phys. Letters 8, 183-185 (April 1966).

J. C. Eidson and Juliana Shaw, "Oscillations and Noise in Indium Antimonide," Microwave Laboratory Report No. 1454, Stanford University (June 1966); Technical Report, RADC-TR-66-462.

B. E. Burke and G. S. Kino, "Helicon Wave Propagation in InSb," Microwave Laboratory Report No. 1537, Stanford University (May 1967); also published in J. Appl. Phys. 38, 4888 (November 1967).

V. THEORY OF CARRIER WAVE PROPAGATION

(M. Chodorow, G. S. Kino, T. Wessel-Berg, and P. Gueret)

A. INTRODUCTION

An interesting and potentially useful property of a plasma is its ability to support a large variety of wave types. Waves in gaseous plasmas have been the object of extensive research for several decades. The subject of waves in a solid-state plasma is a more recent one. The study of such waves is stimulated not only by the fact that material properties can be studied this way, but also by the hope that they may have technological importance in microwave devices such as amplifiers, oscillators, and electronically variable delay lines.

In spite of considerable differences between gaseous and solid-state plasmas, many striking analogies exist between them from the point of view of plasma phenomena. This project was concerned more particularly with plasma properties of conduction electrons and holes in semiconductors and semimetals, both intrinsic and extrinsic. In extrinsic semiconductors one is dealing with one carrier species; in intrinsic semiconductors as well as in extrinsic ones in the presence of high injected carrier densities, there are two species of carriers with equal or nearly equal densities.

The purpose of this project was to examine the different wave types which may exist in a solid-state plasma under a variety of conditions. These conditions are essentially the presence of arbitrarily oriented electric and magnetic fields $\overline{E}_0$ and $\overline{B}_0$. It turns out that the relative orientations of $\overline{E}_0$ and $\overline{B}_0$ in space are an important factor in determining the nature of the existing waves. Cases were studied where only one type of carriers (electrons) was present, and cases where both types (electrons and holes) exist within the material.

This project was initially titled "Transverse Wave Studies." The research during the early stages resulted in five technical reports, listed below. It was from this preliminary work that the present project

evolved. The final technical report on this project (M.L. Report No. 1533) reports the details which are briefly summarized below:

B. RESEARCH SUMMARY

"We concentrated on a type of slow wave called carrier wave because it has a phase velocity equal or nearly equal to the electron drift velocity. Under suitable conditions, these carrier waves can have very little damping or can even grow in space (convective instability). Technologically, this is a very important result since it means that solid-state delay lines or amplifiers can be built using carrier waves. Another possibility which was examined concerned waves whose amplitude grows uniformly in time (absolute instability). In this case, the obvious device application would be a solid-state oscillator. Besides the possible device applications which can be derived, this study was also aimed at finding some sort of reasonable explanation for a now familiar phenomenon known as "microwave emission from InSb."

"We examined a variety of instabilities that may occur in semiconductors or semimetals. In most situations studied, the energy which sustains the instabilities is supplied by an external electric field which drifts the carriers in the solid. In one case, the energy comes from an external pump which perturbs the carrier distribution out of equilibrium and creates some sort of population inversion. Except in one case, all instabilities require the presence of an external magnetic field."

PAPER AND PUBLICATIONS

Tore Wessel-Berg, "Conduction Processes, Normal Modes, and Drift Instabilities in Bulk Semi-Conductors," Microwave Laboratory Report No. 1315, Stanford University (April 1965); Technical Report, RADC-TR-65-393 (November 1965). AD No. 624 089.

Wes Hocks, "Transverse Waves in Accelerated Parallel-Flow Electron Beams with Constant Magnetic Field," Dissertation, Microwave Laboratory Report No. 1323, Stanford University (May 1965).

G. S. Kino, "Carrier Waves in Semiconductors," Microwave Laboratory Report No. 1393, Stanford University (August 1965); Technical Report, RADC-TR-65-347 (1965). AD No. 624 090.

P. Gueret, "Wave Propagation on Crossed Field Electron Beams," Microwave Laboratory Report No. 1359, Stanford University (August 1965).

Tore Wessel-Berg, "The Electron Beam as an Electromagnetic Medium," Microwave Laboratory Report No. 1378, Stanford University (November 1965); Technical Report, RADC-TR-65-530. AD No. 486 688.

P. Gueret, "Wave Propagation and Instabilities in Semiconductors," Dissertation, Microwave Laboratory Report No. 1533, Stanford University (May 1967); Technical Report, RADC-TR-67-339. AD No. 819 155.

VI. EXTENDED INTERACTION KLYSTRONS

(M. Chodorow and B. Kulke)

This project had been underway on the predecessor contract and was nearing completion when the present contract began; the First Semi-Annual Report on this contract reported the completion of the research. At that time a technical report on the whole research project was completed. The abstract of this technical report, by B. Kulke, titled "An Extended Interaction Klystron: Efficiency and Bandwidth," follows:

"The purpose of this work was to investigate the dependence of the efficiency and the saturated bandwidth on the length and the loading conditions of the output resonator, and on the beam velocity, in an extended-interaction klystron. An experimental three-cavity extended interaction klystron, with cavities consisting of resonated sections of ring-bar structure, was built and tested. The experimental tube was designed for pulsed operation near 25 kV at 1100 Mc. The active length of the output resonator was variable between one and five resonant half-wavelengths. The input and the intermediate cavities were made tunable so as to simulate a wide-band stagger-tuned bunching section. Exploratory steps leading up to the final tube design were the investigation of a planar circuit (a stub-supported meander line), and the design, construction, and beam testing of a three-cavity klystron operating near 100 kV at 2800 Mc. All beam tests were carried out on the electron stick, a laboratory electron beam contained in a slender evacuated glass tube which is inserted into the structure to be tested in lieu of an actual beam.

"Data are presented which lead to the following conclusions. As the cavity length is increased, the peak efficiency rises up to a point and then remains constant, while the bandwidth increases proportional to cavity length. As the loading is reduced, for a given cavity length, the efficiency generally rises monotonically until further reduction in loading results in the onset of regenerative cavity oscillations at the

frequency of the design resonance. The necessary suppression of regenerative oscillation in adjacent resonances becomes more difficult as the cavity length is increased, and a basic limitation on cavity length is given by the quality of the coupler, which must be capable of providing uniform and heavy loading over a broad frequency range."

The most significant aspects of this work were summarized and published in a paper by Chodorow and Kulke.

PAPERS AND PUBLICATIONS

B. Kulke, "An Extended-Interaction Klystron: Efficiency and Bandwidth," Dissertation, Microwave Laboratory Report No. 1320, Stanford University (May 1965).

M. Chodorow and B. Kulke, "An Extended-Interaction Klystron: Efficiency and Bandwidth," Microwave Laboratory Report No. 1337, Stanford University (June 1965); also published in IEEE Trans. Electron Devices ED-13, 439-447 (April 1966).

VII. CENTIPEDE TWT

(D. K. Winslow and T. Reeder)

A theoretical and experimental study of the amplitude and phase characteristics of high power, broadband traveling-wave tubes using the Centipede circuit was completed during the first quarter of this contract. A complete technical report was written: T. M. Reeder, "Amplitude and Phase Characteristics of Coupled Cavity Traveling-Wave Tubes," (March 1965). The abstract follows:

"This investigation is a theoretical and experimental study of the amplitude and phase characteristics of high-power, broadband traveling-wave tubes which use the coupled cavity type of slow-wave circuit. A particular tube is studied, one which uses the Centipede circuit. However, the results found here apply to other coupled cavity tubes such as the Cloverleaf or the Long Slot.

The theoretical portion of this report describes a small signal wave theory for the interaction of an electron beam with a chain of coupled cavity resonators. This theory, which describes the coupling between the two fundamental space charge waves of the beam and the forward and backward traveling waves of the circuit, has several advantages for coupled cavity tubes. While the three wave Pierce theory erroneously predicts infinite growing wave gain per unit length at the circuit band-edges, the theory given here does not. An equivalent circuit which is an accurate electrical analogy of the Centipede waveguide is used to represent the coupled cavity circuit. The effect of circuit loss is included. As far as electron beam dynamics are concerned, the coupled cavity is represented by a series of planar interaction gaps, each one periodic length long. The source and load termination of the circuit are represented by resistive impedance. Thus, the theory includes the essential physical features of coupled cavity tubes in a way that is analytically straight forward. The theory is used to calculate the relative rf field amplitude and phase seen at each circuit cavity. By

constructing graphs of cavity field amplitude and phase versus cavity position in the tube, the various types of wave motion existing on the circuit are studied as a function of frequency and tube operating conditions.

"The validity of the wave theory is supported by experimental measurements of the Centipede tube. Measurements of rf field amplitude and phase at each coupled cavity are described for a Centipede tube designed for S-band operation at peak power output in excess of one megawatt. All measurements were performed under small signal conditions. Amplitude and phase measurements were first made with the beam turned off so that the cold attenuation and phase characteristics of the Centipede circuit could be obtained. Later measurements with an accelerating voltage of 100 kV and pulsed beam current of 61 amps showed that the rate of growth and phase shift per cavity of the growing wave could be accurately measured with this experiment. Especially interesting were measurements at frequencies near the lower cutoff of the Centipede circuit. Beating waves with phase shift per cavity close to the beam phase were seen in the output section of the tube despite high circuit loss of 2 dB/cavity at this frequency."

A paper based on this work was later submitted for publication. Earlier related work on the predecessor contract resulted in two publications pertinent to this project.

PAPERS AND PUBLICATIONS

T. M. Reeder, "Amplitude and Phase Characteristics of Coupled Cavity Traveling-Wave Tubes," Dissertation, Microwave Laboratory Report No. 1307, Stanford University (March 1965).

T. M. Reeder, "An Equivalent Circuit for Coupled Cavity Waveguides," Microwave Laboratory Report No. 1341, Stanford University (April 1966); submitted to IEEE Trans. PGMTT.

A. J. Bahr, "A Coupled-Monotron Analysis of Band-Edge Oscillations in High-Power Traveling-Wave Tubes," Microwave Laboratory Report No. 1254, Stanford University (October 1964); also published in IEEE Trans. PGED ED-12, 547 (October 1965).

A. J. Bahr, M. Chodorow, and D. K. Winslow, "A High-Power Electron Stick," Microwave Laboratory Report No. 1370, Stanford University (September 1965); also published in IEEE Trans Electron Devices ED-13, 510-511 (May 1966).

VIII. PERIODIC FERRITE DEVICES

(M. Chodorow, H. J. Shaw, and W. F. Egan)

A. INTRODUCTION

A theoretical and experimental investigation of a new approach to variable signal delay at microwave frequencies was conducted. The principal feature of this approach was the use of an array of yttrium iron garnet signal crystal spheres as a periodic propagating circuit. An applied dc magnetic field controlled the center frequency and width of the passband. Varying the magnitude of this field changed the velocity of propagation of the microwave signal along the array for a given frequency. This system has interest as an electronically controlled delay line in the nanosecond-to-microsecond delay range, and also as a YIG frequency filter whose passband width as well as center frequency are electronically variable.

B. RESEARCH SUMMARY

A theoretical analysis has been made of the propagation of rf magnetization along a linear array of ferrite spheres, which results from magnetic dipolar field coupling between the various spheres. Using the differential equations of motion for magnetization in ferrites, theoretical propagation and attenuation constants and group velocities were calculated, including the relevant practical effects of dissipation in the ferrite samples, cylindrical shielding enclosures, and multiple neighbor coupling. Basically, the propagation on the array changes from backward wave propagation (oppositely directed phase and group velocities) when the dc magnetic field is oriented along the array axis, to forward wave propagation when the dc field is oriented at right angles to the array axis. Computer generated curves for a variety of cases have been calculated and may be found in the technical report by Egan.

Two experimental YIG arrays, one having 5 spheres and one having 9 spheres, were constructed. The YIG spheres had diameter of 0.048

inches, were spaced 0.120 inches on centers, and had isolated linewidths of 0.36 oersteds. An array fitted with very loosely coupled input and output waveguide couplers was used for determination of the dispersion curve by means of resonance measurements. Such measurements can accurately determine the dispersion curve which applies with perfectly matched couplers, without the necessity of designing such couplers. Close agreement was obtained between theoretical and measured dispersion characteristics. The details are given in the technical report by Egan and in the paper by Egan, Shaw, and Chodorow. An array was also fitted with input and output couplers tightly coupled to the external waveguides, and steps were taken to approximately match these to the ferrite array.[7] The array was operated at S-band in the range of 3500 to 3900 MHz.

It was not the purpose of this project to undertake engineering design of broadband couplers which would be matched over the passband. However, it was found by tuning the couplers separately at each point across the passband that the insertion loss could be held reasonably flat across the passband, and that insertion loss for the structure was generally in the range of 15 dB. The passband width, in terms of applied dc magnetic field variation required to take the structure from one end of the passband to the other, was around 30 oersteds, which corresponds to a frequency bandwidth of some 8[illegible] MHz at constant dc magnetic field. Measured signal delay in the structure varied from some 50 nanoseconds near band center to some [illegible] nanoseconds near the band edges. This is less by a factor of two than the delay variation predicted theoretically for this particular structure. However, in general, time delays which lie in the range of short delays encountered here, and which vary rapidly with field and frequency, are difficult to measure. Special techniques were employed in the measurements, using two independent systems, but the resulting accuracy is limited.

The outcome of the measurements on the experimental YIG arrays is that the passband width has been well verified, by both resonance measurements and transmission measurements, and that measured time delays are of the correct order.[9] More detailed information on the transmission measurements is incorporated in a technical report to be issued under the successor

contract. Some quantitative considerations concerning possible applications to variable delay lines, and also to electronically variable propagating circuits for microwave amplifiers, are given in the Egan report.

PAPERS AND PUBLICATIONS

W. F. Egan, "Microwave Propagation in Periodic Ferrite Structures," Dissertation, Microwave Laboratory Report No. 1535, Stanford University (May 1967); Technical Report, RADC-67-377 (August 1967). AD No. 819 850.

W. F. Egan, H. J. Shaw, and M. Chodorow, "Propagation and Variable Delay on a Periodic Circuit of YIG Spheres," Microwave Laboratory Report No. 1487, Stanford University (December 1966); also published in J. Appl. Phys. 38, 1230 (1 March 1967).

IX. ADIABATIC MAGNETOELASTIC CONVERSION IN THE TIME DOMAIN

(B. A. Auld, J. Collins, and H. R. Zapp)

A. INTRODUCTION

If the velocity of propagation in a ferrite medium varies with time, the wavelength of a propagating signal is conserved, while the signal frequency varies with time. In a medium where both the impedance and the velocity of propagation are time-varying, a reflected signal at a shifted frequency will also be produced. These effects have been well-known for several years, but no experiments had been reported at the commencement of this project. In this project we were concerned with the effects of a time-varying applied magnetic field on magnetoelastic waves propagating in a ferrite medium.

Magnetoelastic wave propagation in ferrites provides an ideal means for realizing such effects experimentally at microwave frequencies, since the short wavelength of these waves allows the use of small samples and the time variation can be induced by means of a time-varying magnetic field. Another advantage of the ferrite medium is that the magnetoelastic waves are hybrid waves extending over a range from pure spin waves to pure acoustic waves. It is therefore possible to convert an acoustic wave into a spin wave at the same wave number, and vice versa, by using a time-varying magnetic field. A spin wave has a group velocity which is several orders of magnitude smaller than an acoustic wave; by thus controlling the time spent in the spin wave state, storage of a pulse in the medium is permitted. Other possible signal processing functions which might be realized in a time-varying magnetoelastic medium are: (1) frequency translation of pulses, (2) frequency coding of pulses — for example chirping, (3) pulse stretching or shrinking, and (4) reversal of a pulse waveform in time.

B. RESEARCH SUMMARY

Using as a model the simple time-varying, spatially uniform transmission line including losses, a general solution was obtained which illustrated the general limitations on the time variation:

(1) The duration of the time variation must be less than the relaxation time of the wave.

(2) Appreciable reflection occurs only when the duration of the time variation is less than a period of the wave (see M. L. Report No. 1582).

By approximating a gradual change in the applied magnetic field as a sequence of small discrete steps, relations were obtained for the reflection coefficient of a pure spin wave traveling at an arbitrary angle. In the same manner reflection and scattering into other modes was evaluated for a magnetoelastic wave propagating parallel to the magnetic field.

It was concluded from these results that reflection — and consequent time reversal of a pulse — would be difficult to obtain at microwave frequencies. In the usual experimental arrangement, the ferrite sample is saturated magnetically; the internal magnetic field has a time-independent spatial variation. Under these conditions a separation of variables solution has been obtained for a spin wave propagation parallel to the applied field (see M. L. Report No. 1582).

Four basic experiments were performed under this project:

(1) Frequency translation of pure spin waves, with a shift of 550 MHz. was obtained at L band using an applied field pulse of approximately 200 Oe and spatially orthogonal wire antennas for coupling (see M. L. Report Nos. 1492 and 1506).

(2) Frequency translation and partial mode conversion of magnetoelastic waves was observed (see M. L. Report No. 1501), using a piezoelectric film coupler on rods of YIG and Ga-substituted YIG.[7] The results were in good agreement with theory.

(3) Frequency modulation (chirping), with subsequent pulse compression, inversion and expansion, has been observed (see M. L. Report No. 1506). In this experiment the signal is coupled in by

means of a wire antenna and the magnetic field pulse is applied at a time when the signal pulse is in the magnetoelastic region.[8] Pulse compression ratios up to 35 were achieved, and substantial agreement with theory was obtained (see M. L. Report No. 1522).

(4) Variable magnetoelastic delay up to 50 μsec was obtained at L band and room temperature (see M. L. Report No. 1509), by using the pulsed magnetic field as a gate which removes the turning point from a wire excited ferrite rod.[8]

Magnetoelastic wave propagation in a time-varying ferrite medium provides a means for realizing rather complicated signal processing functions in a simple compact structure. In an effort to make systems designers aware of these new possibilities a review article directed toward the non-specialist has been published: B. A. Auld, J. H. Collins, and R. Zapp, "Microwave Signal Processing in a Nonperiodically Time-Varying Magnetoelastic Medium," Proc. IEEE 56, 258 (March 1968).

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B. A. Auld, J. H. Collins, and H. R. Zapp, "Microwave Signal Processing in Time-Varying Magnetoelastic Medium," Microwave Laboratory Report No. 1582, Stanford University (September 1967); also published in Proc. IEEE 56, 258 (March 1968).

B. A. Auld, J. H. Collins, and H. R. Zapp, "Spin Wave Frequency Conversion by Adiabatic Field Pulsing," Microwave Laboratory Report No. 1492, Stanford University (December 1966); also published in Electr. Letters 3, 35 (January 1967).

B. A. Auld, J. H. Collins, and H. R. Zapp, "Adiabatic Time Domain Conversion of Hybrid, Magnetoelastic Waves in YIG," Microwave Laboratory Report No. 1501, Stanford University (January 1967); also published in Appl. Phys. Letters 10, 186-188 (15 March 1967).

B. A. Auld, J. H. Collins, and H. R. Zapp, "Frequency Modulation and Translation with Magnetoelastic Waves in YIG," Microwave Laboratory Report No. 1506, Stanford University (February 1967); presented at IEEE G-MTT International Symposium, Boston May 1967.

J. H. Collins and H. R. Zapp, "Theoretical Considerations of Time Delay for Bias-Field Pulsing in YIG," Microwave Laboratory Report No. 1522, Stanford University (March 1967); also published in Electr. Letters 3, [illegible] (May 19[illegible]).

R. C. Addison, J. H. Collins, and H. R. Zapp, "Variable Magnetoelastic Delay to 50 μsec at L-Band," Microwave Laboratory Report No. 1509, Stanford University (February 1967); also published in Proc. IEEE 55, 697 (May 1967).

X. THEORY OF THE GUNN EFFECT

(G. S. Kino, K. J. Harker, R. Dunsmuir, and P. Robson)

A. INTRODUCTION

The purpose of this project was to obtain computer solutions to the Gunn effect equations. The model chosen to represent the GaAs sample was time-dependent, spatially finite and one-dimensional, and capable of being characterized by a varying donor density. The provision for varying donor density profiles allowed us to simulate the contact region at the sample ends with a region of high donor density.

B. RESEARCH SUMMARY

The normalized equation for the electric field is parabolic and subject, thereby, to numerical instabilities unless the time increment is made prohibitivity small. It was found necessary, therefore, to solve this equation by the implicit finite difference method, which is known to be absolutely stable. The simultaneous set of nonlinear algebraic equations which arise from the implicit formulation were solved by means of an interaction method which depended, in terms, on the use of a relaxation parameter. A theory was evolved for this relaxation parameter which uses a variable depending on the time-step, which allowed us to continually determine it as a function of the evolving solution. Full details for the theory are found in K. J. Harker, "Numerical Solution of the Gunn Effect Equations."

The numerical solution on the computer of the normalized equation for the electric field allowed us to observe the detail of domain growth and propagation. Early results with the program showed disagreement with invariant domain theory, which was known to be correct. An exhaustive analysis of the computer program showed that the difficulty could be overcome by writing the terms in the basic equation as perfect differentials. When the appropriate changes were made in the computer program, good agreement was obtained with the invariant domain theory.[8]

It was determined that one always obtains an accumulation layer where the doping profile is constant with distance. Since, on the other hand, one always observed dipole layers in experiments on GaAs, a major effort was made to determine under what conditions dipole solutions could be obtained with the computer simulation. As reported by others using computer programs, it was observed that a notch in the donor density profile would cause the generation of dipole domains. It was also found that an upward linear grade in the donor density from cathode to anode would also cause the formation of dipole layers.

A study made at another laboratory, to evaluate with the computer the validity of Gunn's experiment,* was used by us to determine the conduction current density curve of GaAs. A set of parameters was chosen for our computer program which simulated a range of conditions encompassing those used by Gunn. Voltage pulses of various widths were applied and the current density measured. For pulses in the range used by Gunn, the current density differed from 10 to 50% from the theoretical conduction current density.

It has been experimentally observed by several workers that the reversal of voltage polarity has a marked effect on the current-voltage curves of GaAs, especially just below threshold. A study of this was made on the computer by applying a fixed voltage to linearly graded samples and observing the limiting current through the sample. This process was carried out for donor density profiles both increasing and decreasing toward the anode in a sequence of increasing applied voltages. Below threshold field the current density for donor density increasing toward the anode was almost identical to but slightly greater than the case of decreasing density. At threshold, however, domain formation occurred for the former case and the corresponding conduction current density dropped abruptly downward below that for the latter case, which exhibited in domain formation. This caused a large difference between the curves, as expected. One must conclude from this study that any marked deviation in the two curves is primarily due to domain formation.

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*J. S. Gunn and B. J. Elliott, IBM Research Note NC634 (Thomas J. Watson Research Center, Yorktown Heights, July 18, 1966).

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K. J. Harker, "Numerical Solution of the Gunn Effect Equations," Microwave Laboratory Report No. 1463, Stanford University (August 1966).

XI. EXPERIMENTAL STUDIES OF GUIDED ACOUSTIC WAVES

(H. J. Shaw and H. M. Gerard)

A. INTRODUCTION

The eventual aim of this project is to experimentally study a type of acoustic propagation which has not yet been reported at microwave frequencies. This involves guided acoustic wave propagation in thin films, in which the waves propagate parallel to the plane of the film. At lower ultrasonic frequencies, guided waves in self-supporting metal strips have seen important application as pulse compression filters. This same function, as well as other microwave transmission signal processing functions, should be possible using dielectric films deposited upon suitable dielectric substrates and the construction is compatible with integrated circuit techniques. Also, traveling wave amplifiers using these waves may be possible, using electrons drifted in the film to interact with the guided acoustic wave.

The activity to date has been concerned with development of the necessary components for the guided wave experiment, particularly transducers for excitation of the waves, and deposition systems for preparation of the films. The transducers will also be directly applicable to surface wave delay lines and related devices at both UHF and microwave frequencies, in addition to their application to the guided wave objective of this project.

B. RESEARCH SUMMARY

It may be useful to first describe the nature of the eventual guided wave experiments that are planned under the successor contract, before describing the work done to date on the development of components required for these experiments. At microwave frequencies, acoustic wavelengths are in the micron range. Evaporated thin films having thicknesses in this range are readily deposited. The waves of interest would propagate parallel

to the plane of the film, and the propagation characteristics are strongly influenced by the boundary conditions formed by the top surface of the film and by the film-substrate interface. The waves are in general dispersive and their propagation velocity and dispersion depend upon the thickness of the film and upon the frequency.*

The basic procedure to be followed in attempting to observe guided waves in films will be to start with the crystalline substrate on which the film is to be evaporated, which will contain transducers (discussed below) for the excitation and detection on Rayleigh surface waves along the substrate surface. The substrate will be placed in the vacuum system for deposition of an SiO film on a portion of the substrate surface which carries the surface wave. The surface wave will be continuously monitored as the film deposition is carried out. This will allow measurement of propagation constant and signal delay as a function of film thickness. With this procedure it should be possible to cover the range from zero film thickness (where the wave is a pure non-dispersive surface wave with energy entirely in the substrate) to thicker films where the energy is largely in the film and maximum dispersion is observed. For still thicker films, the waves will be essentially non-dispersive surface waves propagating on the top surface of the film

The vacuum station for this work is presently under design. Initial experimental work will be done with signals at 100 MHz, and carried to successively higher frequencies after experience with the wave properties has been obtained.

The transducers are inter-digital comb structures of the type analyzed by Coquinn and Tiersten,† deposited directly on the piezoelectric crystalline substrate. Both quartz and lithium niobate substrates have been employed. The lithium niobate crystals are grown at the Center for Materials Research at Stanford University.

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*Quarterly Status Report No. 34 for Contract Nonr 225(48), Microwave Research," Microwave Laboratory Report No. 1592, Stanford University (October 1967).

†G. A. Coquinn and H. F. Tiersten, J. Acoustic Soc. Am. 41, 4 (Part 2) 921 (1967).

The present transducers are produced by photo-etching of deposited aluminum films in a photo-etch facility established here for this purpose. The transducers have 30 finger pairs with periodicity of 33 microns (two fingers plus two spaces), for fundamental mode operation in the vicinity of 100 MHz. Initial operation of these devices has demonstrated 25 dB total insertion loss at 118 MHz.[10] This includes contributions due to bi-directional properties of the transducers (~ 6 dB), electrical impedance mismatches (~ 6 dB), and losses in the electrical bonds to the comb electrodes, all of which are subject to elimination, and this will be undertaken as a next step under the successor contract, which should very substantially reduce the insertion loss. The above insertion loss also contains the acoustic transmission loss in the substrate, which is unknown at this time, but which is known to be strongly influenced by surface contamination. The cw measurements of the electrical input impedance of the transducers as a function of frequency, in the neighborhood of acoustic synchronism, will allow separation of the various sources of insertion loss, and should provide very accurate measurements of these quantities.

XII. YIG DELAY LINE STUDIES

1. DOUBLE-ENDED YIG VARIABLE DELAY LINE (B. A. Auld, H. J. Shaw, C. F. Quate, and D. K. Winslow)

Magnetoacoustic waves in single crystal ferrites offer the simplest know mechanism for achieving variable microsecond delays at microwave frequencies. Practical utility of these devices has been limited by the fact that in their usual form they are basically one port, or single-ended, devices. The present project was concerned with a new scheme,* for overcoming this problem (see M. L. Report No. 1475). The approach we used utilized the acoustic couterpart of optical quarter-wave plates, with the objective of converting a single-ended YIG delay line into what is basically a double-ended device.

Experiments performed on this system at Stanford gave very poor results. This was attributed to the poor quality of the polystyrene and phenyl salicilate bonds used to fix the quarter-wave plate to the ends of the YIG. However, the theory of this device stimulated experiments elsewhere, which were successful.† This was due to the use of high quality optical contact bonds (90% transmission at 1 GHz) for the quarter wave plates.

2. ELECTRONIC FOCUSING IN ACOUSTIC DELAY LINES (B. A. Auld, J. H. Collins, and D. Webb)

This project, which evolved from the preceding one, is concerned with another approach to the realization of a double-ended YIG delay line. In principle such a device might be realized by using a YIG sample which is shaped to give a concave-upward internal field profile. However, it has

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*B. A. Auld, C. F. Quate, H. J. Shaw, and D. K. Winslow, "Double-ended YIG Variable Delay Line," Conference on Electron Device Research, Pasadena, June 1966.

†H. Van de Vaart and H. Smith, "High Efficiency Polarization Reversal of Magnetoelastic Waves in YIG by Optical-Contact Bonding of YAG Disks," Appl. Phys. Letters 9, 439 (1966).

been shown theoretically** and experimentally†† that defocusing of the magnetoelastic beam prohibits operation in this configuration. Successful two-port operation had previously been achieved by using a profile which is concave upward at the center of the rod and concave upward at the ends.†† The optical contact bonds described above† permit the use of a simpler arrangement. Two YIG rods are optical contact bonded to opposite ends of a YAG rod. The field profiles in the YIG rods are then of the convex-upward shape required for focusing of the magnetoelastic beam, and the acoustic waves is transmitted from one YIG rod to the other through the YAG rod.

An experimental model of this device gave variable delay from 4 to 8 μsec with an insertion loss of 47 dB at 4.7 μsec delay.*** In the course of these experiments strong evidence was found for the excitation of the YIG at the end face of the rod rather than at the turning point (M. L. Report No. 155[illegible]). This should have important implications for the design of broad band coupling into the YIG structure.

A paper on the relative merits of the YAG-YIG-YAG line and the YIG-YAG-YIG line as pulse compression filters has also been prepared (M. L. Report No. 1552).

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** B. A. Auld, "Geometrical Optics of Magnetoelastic Wave Propagation in a Nonuniform Magnetic Field," Bell Sys. Tech. J. 44, 495 (1965).

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XIII. MAGNETICALLY DEPENDENT SOUND WAVE INTERACTIONS

(G. S. Kino, J. Ruch, and R. Route)

A. INTRODUCTION

In piezoelectric semiconductors, such as the III-V compounds, acoustic waves can interact with mobile carriers within the material. Under the proper conditions, it is possible to transfer energy from a background of moving carriers to an acoustic wave propagating through the medium.* Such amplification of acoustic waves has been observed in several materials, notably CdS and GaAs. However, acoustic amplifiers made from these materials suffer from a problem of power dissipation. The drift fields required to produce carrier drift velocities a few times the sound wave velocity, where acoustic amplification can occur, cause a large dc power dissipation. In the past this power dissipation has required pulsed drift field operation.

It has now been shown theoretically[10] that, in the high mobility materials, the presence of a transverse magnetic field can have a very significant effect upon the power dissipation limitation. For example, at the condition of maximum acoustic gain, the addition of a transverse magnetic field of a few kilogauss can cause a 5x fold reduction in dc power dissipation. Thus, using a high mobility material such as n-type InSb at 77°K and a transverse magnetic field, cw acoustic wave amplification should result.

Our aim has been to study the effect of a transverse magnetic field on sound wave propagation in InSb and to use this information in designing and constructing a cw acoustic amplifier. We experimentally demonstrated the effect of the magnetic field. Furthermore, we included the effect of the magnetic field in the small signal theory of sound wave amplification in a piezoelectric semiconductor and compared it in an indirect fashion with experimental results.

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* D. L. White, "Amplification of Ultrasonic Waves in Piezoelectric Semiconductors," J. Appl. Phys. 33, 2[illegible] (1[illegible]).

B. RESEARCH SUMMARY

The research on this project includes an experimental check of the small signal theory of sound wave amplification. Because only the final quarterly period of the contract was devoted to this project,[10] it was not possible to construct an actual acoustic wave transmission device. Instead, a slightly indirect method was used. A bar of InSb at 77°K placed in transverse magnetic field will generate acoustoelectric domains with an applied drift field. We assume that acoustoelectric domains result from amplification of background thermal noise. Using the small signal theory, one can approximate the threshold of acoustoelectric domain formation and compare the theoretical behavior with experiment. This was done and quite good agreement was observed.[2] We feel that the effect of the magnetic field and the process of acoustoelectric domain formation are now well understood. It was also demonstrated that, with a transverse magnetic field, an InSb bar will generate acoustoelectric domains on a cw basis. Thus an acoustic amplifier which would operate below the point of domain formation should certainly operate cw also. Such a device will be constructed as a part of the program of the successor contract. The device will be a shear wave amplifier, operating at 77°K in a transverse magnetic field and might be used as a microwave acoustic amplifier or as a loss compensated microwave delay line with delay times approaching 10 μsec.

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13. ABSTRACT

The objectives for the research program under this contract were to conduct a theoretical and experimental investigation of microwave techniques with a view toward development of devices applicable to surveillance systems; the emphasis was primarily directed toward requirements of phased array radar systems. This report, covering the period November 1964 through October 1967, summarizes the principal research findings on the following projects, conducted for varying lengths of time on this contract:

I. Thin Film Transducers
II. Acoustic Wave Devices
III. Carrier Wave Propagation
IV. Whistler Mode Propagation in Solids
V. Theory of Carrier Wave Propagation
VI. Extended Interaction Klystrons
VII. Centipede TWT
VIII. Periodic Ferrite Delay Lines
IX. Adiabatic Magnetoelastic Conversion in the Time Domain
X. Theory of the Gunn Effect
XI. Guided Acoustic Waves
XII. Delay Line Studies
XIII. Magnetically Dependent Sound Wave Interactions

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13. Continued

Future reports concerning the projects to be continued will be found in reports on Contract F30602-68-C-0074, "Microwave Acoustic and Bulk Device Technique Studies" which is a direct continuation of this effort.